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Military Applications of Fiber Optics Technology

Joseph F. Benzoni, David T. Orletsky

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PREFACE

This Note presents an overview of fiber optics technology and potential military applications of that technology. It puts into historical perspective the birth and exponential growth of fiber optics into a commercial success that has virtually replaced other means of long-distance telecommunications. It discusses general advantages and disadvantages in the use of fiber optics, setting a backdrop from which applications of the technology to military systems can be presented. This work was funded by RAND-sponsored research.

This Note considers several categories of developmental and proposed military systems that use some facet of fiber optics technology; however, it makes no attempt to analyze these systems in terms of technical feasibility, cost, or military utility. This work is presented to provide the reader with an appreciation of the technology's potential to alter dramatically certain aspects of military operations in the very near future.

The appendix to this Note contains a basic tutorial on some of the principles of fiber optic information transfer. It may be of interest as technical background information. Keywords: Fiber Optics, Physics, Glass Fibers, Telecommunications, Optical Fibers, Sensor Systems, Information Transmission, Optoelectronic Devices.

SUMMARY

A technological revolution in information transmission has occurred within the last two decades. Fiber-optics--hair-thin glass fibers carrying laser light--is now the preferred mode for commercial long distance telecommunications. This revolution, enabled by the solid state laser and the production of optical fibers with sufficiently low losses, is currently expanding into other related areas such as sensors and computing. This Note examines the state of the art of fiber-optics and assesses the military implications of that technology.

The attributes of optical fiber information systems make them even more desirable for military than commercial applications. These attributes include immunity to electromagnetic interference, relative security from eavesdropping, the ability to span long distances without repeaters, and low cable weight. However, military applications impose additional requirements on fiber-optic systems which have limited their viability. These requirements include wider operating and storage temperatures, and the ability to withstand severe vibration, shock, and other mechanical stress.

An additional impediment to the military use of fiber-optics is the lack of readily available hand tools, parts, training, etc. for installation, maintenance, and repair of systems in the field. This situation is changing, however, due to the proliferation of commercial systems. On balance, the requirements for military applications are being successfully addressed. In general, the technologies which need enhancement to further enable military applications are simply more rugged versions of commercial technologies with increased tolerance to physical abuse.

In addition to communications, this technology could provide the military with substantial benefit in a variety of functions. The most promising applications are in weapon systems, sensor and surveillance systems, optical computing systems and information transmission aboard vehicles.

One weapon system currently under development for the Army is the fiber-optic-guided missile (FOG-M). This is a medium range, lock-on-after-launch weapon system to be used against helicopters and ground vehicles. A similar fiber optic guided missile system is also under development for the Navy.

Fiber optic sensors offer great promise for a variety of sensing and surveillance applications due to their extremely rugged characteristics and ability to monitor a wide range of physical parameters. For example, the high degree of sensitivity obtainable with an acoustic interferometer made from optical fiber could vastly improve underwater submarine surveillance. In addition, the rugged nature of these sensors could provide a substantial reduction in maintenance and replacement costs.

Fiber-optics holds great promise in the field of computing. An optically switched computer is theoretically capable of computing speeds which are several orders of magnitude greater than electronically switched machines. For such a device to become a reality, however, small optical switches with low power consumption are needed.

A leading avenue for applying fiber optics technology to the field of computing is neural networks. Virtually every major defense contractor is pursuing research efforts in this new area. Many military applications lend themselves especially well to the use of neural networks, including target recognition, sonar classification, and target tracking. Designing a neural network to accomplish these tasks would have profound impact on current and future weapon systems.

The inherent advantages of fiber-optics make them especially well suited for use aboard military and commercial vehicles. Ground, sea, and air vehicles could all benefit from the application of this technology. With the emphasis of aircraft design on lighter vehicles and the use of composites for fuel savings and radar absorption, fiber optics provides an avenue of great promise. The fibers are much lighter than copper cable and are essentially immune to electromagnetic interference.

The trends in fiber-optic devices are towards lower-loss fibers with greater resistance to damage, semiconductor lasers with low dispersion and greater tunability, and a variety of optical control devices with high speed and which integrate well with electronics. The military can only benefit as such developments continue.

ACKNOWLEDGMENTS

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TABLES

ACRONYMS

AAWS-M	Advanced Anti-armor Weapon System-Medium
APD	Avalanche photodiode
CRT	Cathode ray tube
DARPA	Defense Advanced Research Projects Agency
DNA	Defense Nuclear Agency
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
FET	Field effect transistor
FOFA	Follow-on-forces attack
FOG	Fiber optic gyroscope
FOG-M	Fiber optic guided missile
FOG-S	Fiber optic guided skipper (Navy FOG-M)
HMMWV	High mobility multipurpose wheeled vehicle
IDOC	Intrusion detection optical communications
IIR	Imaging infrared
ILD	Injection laser diode
LED	Light emitting diode
MLRS	Multiple launch rocket system
NASP	National aerospace plane
NLOS	Nonline of sight
NSA	National Security Agency
PIN	Positive-intrinsic-negative
RADC	Rome Air Development Center
RFI	Radio frequency interference
SAGM	Separate absorption, grading, multiplication
SDIO	Strategic Defense Initiative Organization
SEED	Self electro-optic effect device
TBM	Tactical ballistic missile
TOW	Tube launched, optically tracked, wire-guided
UAV	Unmanned aerial vehicle

I. INTRODUCTION

The propagation of light through hair-thin glass fibers is rapidly becoming the preferred mode of transmitting information, with major long-haul telecommunication systems operating between most U.S. cities,[1] a transatlantic system recently made operational,[2] and a transpacific system scheduled to go into service within the year.[3] Essentially all new long-distance telephone cables installed in the United States are optical ones.[4] And trial systems are about to be deployed for "fiber-to-the-curb," which will bring voice, data, and video services over fiber optic cables to residential users.[5] It is believed that the current proliferation of lightwave applications is only the leading edge of what will surely be a larger revolution, with optics spreading more and more into areas that were traditionally the domain of electronics.

Fiber optics, which is part of a larger or more general field called photonics, is concerned with the use of glass fibers carrying photons to complement or even replace electron-carrying wires in certain communications, computer, or control applications traditionally carried out by electronics. As noted previously, this technology is now well established in long-distance fiber optic telecommunications and rapidly growing in other areas of great importance to society, including sensors, information storage, and information processing.

In the commercial world, the present size of the field of photonics is several billion dollars, with potential for growth to more than $100 billion.[6] It is generally viewed as one of the key technologies of the information age, because of the great

[1]By 1992, the Ameritech network alone expects to have 300,000 miles of fiber optic cable in place. (American Information Technologies Corporation is one of the Bell system "seven sisters" that operates in the Great Lakes Region.)

[2]*Los Angeles Times*, 26 February 1989, Part III, p. 3.

[3]"Telecommunications News," *Telecommunications*, Vol. 23, No. 2, February 1989, p.11.

[4]John S. Mayo, "Materials for Information and Communication," *Scientific American*, Vol. 253, No. 4, October 1986, pp. 59–65.

[5]Victoria A. Mason, ed., *Telecommunications Reports*, Vol. 55, No. 8, 27 February 1989, p. 20.

[6]*Photonics: Maintaining the Competitiveness in the Information Era*, National Research Council, National Academy Press, Washington, D.C., 1988, p. 7.

information capacity it offers and the potential for parallel processing. In addition to communications, fields such as optical signal processing and information storage also have considerable potential for military applications. Thus the field of photonics is viewed as strategically important both commercially and militarily.

The objective of this paper is to survey the current state of fiber optics technology and to present a perspective on this field from which to assess current and potential new areas of application for the military. Although the advantages inherent in using this technology would suggest that great investments to integrate the technology into the military would currently be under way, this is not necessarily the case.

Certain attributes of optical fiber systems have greater importance in military applications than in commercial applications. These attributes include immunity to electromagnetic interference, relative security from eavesdropping, spanning of long distances without electronic repeaters, and low cable weight. Conversely, military applications impose additional requirements on fiber optic systems, such as wider operating and storage temperature ranges; ability to withstand severe vibration, shock, and other mechanical stress; and robustness of system performance in the presence of multiple simultaneous subsystem failures.

These and other more strenuous specific requirements have called into question the viability of optical fibers in certain applications. As an example, the set of requirements for fiber-guided missiles includes fiber cables that are radiation resistant, that can operate over a wide temperature range without excessive attenuation increase due to a phenomenon called microbending, that are capable of sustaining high strains without breaking, and that can withstand severe chemical environments. Although these requirements may not necessarily be more stringent than the requirements for certain commercial applications such as oil drilling operations, they have led to design challenges for the technology.

On balance, the requirements for military applications are being successfully addressed. In general, the technologies that need enhancement to enable military applications are simply more rugged versions of commercial technologies with increased tolerance to physical abuse. Examples of enabling commercial technologies that could be developed within the next five years include fiber cables with low loss and low dispersion at 1.3 and 1.5 micron wavelengths, and with low microbending loss and high strength; transmitter modules with high power output, narrow linewidth, long lifetime,

tolerance to elevated temperatures, and low power consumption; receiver modules with high sensitivity, bandwidth, and linearity; and passive components for wavelength multiplexing and demultiplexing.[7]

In another important area of application, fiber optic sensors for general industrial use have largely been restricted to applications in which their small size has made them convenient replacements for conventional photoelectric devices. However, rapid advances in fiber optic transmission systems, coupled with novel but effective transducing technology, have set the stage for a powerful class of fiber optic sensors.[8] Optical fibers have applications as extremely sensitive sensors of a wide range of physical parameters including temperature, pressure or sound waves, and electric and magnetic fields. Although these sensors have been shown to be accurate while operating in harsh environments, the barrier to their increased use stems from a lack of standardization.

The focal plane array is a second type of optical sensor that has led to a revolution in data handling and processing of radiation-induced signals in the infrared and visible regions. These devices have been used in both strategic and tactical military applications as well as consumer applications, although continued research is needed on materials and software to support their data acquisition and processing. Research and development of fiber optic sensors for the military has been dominated by DARPA and the Navy,[9] and the military will in all probability perfect the sensitive surveillance types of fiber sensors, which will then diffuse to the commercial marketplace over time.

Finally, the complementariness between electronics and photonics should be noted. In some commercial applications, such as long-distance, high data rate transmission, fiber optics is the dominant technology. Other applications, such as computing and switching, remain the domain of electronics because manufacturing techniques have been developed to obtain very high levels of integration of electronic circuits. Furthermore, common control functions readily performed with electronics have yet to be demonstrated with photonics systems. Fiber optics and electronics will undoubtedly remain complementary, and optoelectronic devices that combine the advantages of photons with those of electrons will gain in importance in the future.

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[7] *Photonics: Maintaining the Competitiveness in the Information Era*, p. 16.

[8] R.F. Coulombe, "Fiber Optic Sensors—Catching Up With The 1980's," *Sensors*, December 1984, pp. 5–11.

[9] Victor C. Dawson, Peter L. Willson, *A Survey of Fiberoptics and Some Military Applications*, Center for Naval Analyses, CRC 516, January 1984.

The trend toward optical technologies will likely continue in consumer markets, industry, and defense systems. The development of materials with the necessary optical properties is the basis of each technology, whether it be ultralow-loss optical fibers for repeaterless spans of high-information-carrying capacity or semiconductor lasers emitting gigawatts of power for destroying missiles. The optics research community is now very diverse, and the materials requirements are generally different for each application.[10]

The remaining sections of this Note are organized as follows. Section II presents background material showing the chronological development of fiber optics technology, as well as a listing of the technology's benefits and drawbacks. Section III describes some current and potential military applications of the technology, noting some of the advantages and disadvantages that fiber optic systems present. Finally, Section IV considers trends in the technology.

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[10]A. M. Glass, "Optical Materials," *Science*, Vol. 235, 27 February 1987, pp. 1003–1009.

II. BACKGROUND

INFORMATION PROCESSING SYSTEMS

The components of any signal processing system, including those using fiber optics, include the transmitters, the transmission medium, and the receivers and other processing or control components.[1] For a typical fiber optic system, these elements are, respectively, lasers or light emitting diodes, optical fibers, and detectors or other types of transducers. The following sections provide a brief background of each of these three component groups and the interrelationship among them.

Fibers

Until the late 1970s, telecommunications systems depended on advances in electronics to provide new capabilities, increased performance, and lower costs. As fiber optics technology emerged from the research lab into large-scale deployment, the impact of this technology on telecommunications was immediate and dramatic. Today, the deployed U.S. base of long-distance (>100 miles) and moderate-distance (5–100 miles) point-to-point fiber systems has an information-carrying capacity far in excess of the total deployed base that existed in the late 1970s. A figure of merit for point-to-point transmission capability is the product of repeaterless span and information-carrying capability, which has increased from 5 km $\times$ 45 megabits/sec in 1979 to more than 40 km $\times$ 560 megabits/sec today.[2]

Although the deployment of fiber optic communication systems has evolved almost entirely within the past decade, the concept of communicating via light waves has been around for more than a century. In 1880, shortly after his invention of the telephone, Alexander Graham Bell was issued a patent on a device for communicating via light.[3]

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[1] Mischa Schwartz, *Information Transmission, Modulation, and Noise*, Second Edition, McGraw-Hill Book Company, New York, 1970, p. 10.

[2] *Photonics: Maintaining the Competitiveness in the Information Era*, National Research Council, National Academy Press, Washington, D.C., 1988, p. 11.

[3] Apparatus for signaling and communicating, U.S. patent 235,199, issued 7 December 1880.

Bell's apparatus, sometimes referred to as the photophone, worked by focusing a beam of sunlight on a reflector that vibrated in response to a sound wave, such as a voice. The modulated light was relayed to a remote detector cell at a distance up to 700 feet away; the detector cell converted the light to electrical current with the same modulation, and this current drove a telephone receiver at the listener's end.[4] Bell's concept was far ahead of the technology available at the time, because the use of sunlight made his line-of-sight communication device subject to atmospheric disturbances such as rain or fog. It proved to be easier to communicate by simply using electrical signals carried by wire strung between sender and receiver.

Open-air transmission still seemed hopeless almost a century later when Bell Labs started a research program in 1960 on long-distance transmission techniques. Effort went into devising shielded waveguiding structures, which would mitigate the effects of weather. The concept of waveguiding structures for light was known as early as 1854, when the British physicist John Tyndall appeared before the Royal Society of London and demonstrated that light could be guided within a jet of water.[5] The first structures built by Bell Labs were conduits, some 8 inches in diameter, containing lenses spaced at 100-meter intervals to refocus the optical beam and change its direction to follow bends. These proved unwieldy and expensive, and other guiding structures were sought. In 1966, it was proposed that silica glass fibers could be made to transmit light with losses less than 20 dB/km, based on measurements made on bulk silica glass.[6] When Corning Glass Works succeeded in manufacturing such a low-loss fiber, glass fibers took the lead as the most practical long-distance conduits.

The term *fiber optics* was coined in the 1950s when fibers were first used in the United Kingdom to develop a flexible fiberscope.[7] When the first fibers with losses less then 20 dB/km were demonstrated in the laboratory and practical light emitting diodes (LEDs) were developed in 1970, it was realized that communication over fibers was a

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[4]Stewart E. Miller, "Lightwaves and Telecommunication," *American Scientist*, Vol. 72, January 1984, pp. 66–71.

[5]John Tyndall, *Proceedings of the Royal Institute of Great Britain*, Vol. 1, 1854, p. 446.

[6]C. K. Kao and G. A. Hockham, "Dielectric-Fiber Surface Waveguides for Optical Frequencies," *Proceedings of the IEEE*, Vol. 113, 1966, p. 1151.

[7]H. H. Hopkins and H. S. Kapany of the United Kingdom developed the fiberscope; *Principles and Applications of Fiber-Optic Communication Systems*, Lightech, Inc., Richardson, Texas, 1984, pp. 2–4.

possibility. Between 1970 and 1976, the loss rate in fibers was reduced to 0.5 dB/km, and the first practical field experiment with a 45 megabits/sec digital system (672 voice frequency channels) was demonstrated. By 1977, the first commercial systems were placed in service.[8] Laser light carried in hair-thin glass fibers has become a preferred mode of transmitting information, whether it be voice signals, video pictures, or one of the many forms of electronically encoded data. Today fiber optic communications systems account for more than 80 percent of U.S. telephone capacity, with an equivalent network of 7.8 billion voice circuit miles,[9] and essentially all new long-distance telephone cables in the United States are optical ones.[10] In addition, in November 1988, a cable with a three-quarter-inch diameter laid over some 3,600 miles on the floor of the of the Atlantic Ocean linked North America and Europe with the first commercial fiber optic communication system.[11] This cable system, which operates at 1.3 micron wavelength and has a regenerator spacing of 40 km,[12] has a capacity of nearly 40,000 two-way telephone calls, can also carry computer data and video signals,[13] and should be contrasted with the latest coaxial cable, laid in the mid-1970s, which has a capacity of 10,000 conversations.[14] Similar fiber optic cables will soon span the Pacific, linking the United States and Asia.[15]

Because optical fibers can carry simple infrared images, temperature information from remote objects can be transmitted over them. Since the fibers can serve as flexible conduits for light energy, they have been used in various applications as laser "guides"

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[8]Robert J. Sanferrare, "Terrestrial Lightwave Systems," *AT&T Technical Journal*, Vol. 166, No. 1, January/February 1987, pp. 95–107.

[9]R. W. Hess et al., *Feasibility of Using Interstate Highway Right-of-Way to Obtain a More Survivable Fiber Optics Network*, The RAND Corporation, R-3500-DOT/NCS, January 1988.

[10]John S. Mayo, ibid., pp. 59–65.

[11]Paul J. Nicholson, ed., "Telecommunications News," *Telecommunications*, Vol. 23, No. 2, February 1989, p. 11.

[12]Tingye Li, "Advances in Lightwave Systems Research," *AT&T Technical Journal*, Vol. 66, No. 1, January/February 1987, pp. 5–18.

[13]"Optical Fiber Systems Ease Load on Satellites," *Los Angeles Times*, 12 September 1988, Part II, p. 5.

[14]John S. Mayo, ibid., pp. 59–65.

[15]William H. Davidson, "Telecommunications Takes Off," *Los Angeles Times*, 26 February 1989, Part IV, p. 3.

for welding and drilling industrial components and as a means to unclog plaque deposits in arteries.[16]

Military applications of fiber optic systems closely parallel commercial applications. Attributes of optical fiber telecommunications systems that have greater importance in military than in commercial applications include immunity to electromagnetic interference, relative security from eavesdropping, spanning of long distances without electronic repeaters, and low cable weight. Additional requirements imposed by military applications of fiber optics include wide operating and storage temperature ranges; ability to withstand severe vibration, shock, and other mechanical stress; and robustness of system performance in the presence of multiple simultaneous subsystem failures.

Lasers

For centuries, light has been an important tool in mankind's technological development, but a marked discontinuity occurred in 1960 with the demonstration of the laser. It was quickly seen that coherent light from lasers had potential application to communications, information processing, medicine and surgery, measurement, materials processing, and a variety of defense and scientific uses. Recent rates of change are especially remarkable in employing light in communications and information processing.

The solid state devices that transmit light into optical fiber waveguides fall into two main classes: the older, more familiar LEDs, which emit incoherent light and injection laser diodes (ILDs), which emit coherent light. Because lasers have high speed, high power, and emit light in a narrow spectral band, they serve well in applications where long continuous runs of cable carry wide bandwidth signals. In applications where low-loss fibers are used in distances less than 1 km, and for data rates under 10 MHz, such as many computer local area networks, LEDs can be used at lower cost.

The history of coherent light emission devices dates back to 1958 when Schawlow and Townes filed a patent[17] on a device now known as the laser (Light Amplification by Stimulated Emission of Radiation). Townes, along with Nikolai Basov and Aleksandr Prokhorov, shared the Nobel Prize in physics in 1964 for this invention. In 1960,

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[16]Martin G. Drexhage and Cornelius T. Moynihan, "Infrared Optical Fibers," *Scientific American*, Vol. 259, November 1988, pp. 110–117.

[17]Masers and Maser communication system, U.S. patent 2,929,922, issued 22 March 1960.

Maiman accomplished the first laboratory demonstration of a laser. Later in the same year, Javan et al. demonstrated the helium-neon laser.[18] In 1962, a number of research teams at separate institutions independently demonstrated the semiconductor injection laser,[19] and the first semiconductor laser was operated continuously at room temperature in 1970. Today, two types of lasers which produce single wavelength light sources, the external cavity laser and the distributed feedback laser have been manufactured and even studied intensively.

Although silicon is now the dominant material for electronics technology, it plays a relatively small role in optics. Silicon is not an efficient light emitter and is not very useful for nonlinear optical devices. The first semiconductor laser ever fabricated was made from gallium arsenide.[20] Because gallium arsenide emits efficiently in the near infrared (at 0.88 μmeters) and optical fibers have a minimum loss at a wavelength almost twice that (1.5 μmeters), it is necessary to fabricate semiconductor lasers from mixtures of materials, most notably indium phosphorus and gallium arsenide. Research continues today into fabrication of ultrathin multilayer devices, with the continued hope of combining optical and electronic devices on the same chip.[21]

Control Devices

Although optical fibers and solid state lasers have enabled the new fiber optics technology, the current limitation to the full implementation of the information-carrying capacity of optical fibers lies in the devices that perform the control functions, such as switching, modulation, and amplification.

To use fully the information-carrying capacity that is already obtainable with optical fibers, control and processing functions must go beyond electronic devices to achieve suitable power and speed characteristics, high parallelism, and conductor-free

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[18] A. Javan, W. R. Bennett, and D. R. Herriott, "Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing a He-Ne Mixture," *Physical Review Letters*, Vol. 6, 1961, p. 106.

[19] See, for example, R. N. Hall et al., "Coherent Light Emission From GaAs Junctions," *Physical Review Letters*, Vol. 9, 1962, p. 366.

[20] I. Hayashi et al., "Coherent Light From GaAs," *Applied Physics Letters*, Vol. 17, 1970, p. 109.

[21] A. M. Glass, "Optical Materials," *Science*, Vol. 235, 27 February 1987, pp. 1003–1009.

interconnections.[22] For example, optical switching devices are capable of about three orders of magnitude improvement in speed over current and even projected theoretical limit electronic devices.[23] In addition, certain functions can be performed directly with simple linear optics. For example, a Fourier transform can be performed with a lens, a fact that was used in early versions of synthetic aperture radar.[24] More general processing functions require devices with a strong optical nonlinearity.

Current control devices are operated either mechanically or electronically, and hence are ultimately limited by their speed, power requirements, and amount of data they can process. That is, since proper processing and routing of signals through a system require that the photonic signals be converted to electronic signals, then amplified and regenerated in noise-free form, unraveled (a process known as demultiplexing), processed, mixed (or multiplexed), and recombined into pulses of photons, the speed limitations arise when the signals are in their electronic form.

In applications where switching speed is important, such as serial information processing, it would be preferable to perform these operations using light alone, because optical devices are capable of about three orders of magnitude faster switching speeds, theoretically could consume up to an order of magnitude less power per switching event, and have the potential to handle many signals in parallel. In addition, optically operated devices will be far less susceptible to electromagnetic interference than their electronic counterparts.

Control of photonic signals using optically switched devices rather than electronically switched ones requires the fabrication of highly nonlinear optically activated devices. The processing capacity of current supercomputers is around $\sim 10^{10}$ bits/sec, with bit rates of 10^{12} appearing feasible with today's technology. To achieve these bit rates with optically activated switches requires materials of higher optical nonlinearity.[25]

There are laboratory examples of nonlinear devices that show promise, such as the electro-optic waveguide switch (also called an optical crossbar). These devices,

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[22]A. M. Glass, "Materials for Optical Information Processing," *Science*, Vol. 226, 9 November 1984, pp. 657–662.

[23]John S. Mayo, "Materials for Information and Communication," pp. 59–65.

[24]Leonard J. Porcello, "Optical Processing Operations in Synthetic-Aperture Radar Systems," *SPIE*, Vol. 128, 1977, pp. 108–117.

[25]A.M. Glass, "Materials for Optical Information Processing," pp. 657–662.

fabricated from lithium niobiate, have demonstrated the capability to optically switch up to 4 input fibers into 4 output fibers or 1 input fiber into 16 output fibers. Other semiconductors, such as gallium arsenide (GaAs), indium phosphorus (InP), and certain ferroelectric materials, also show promise as electro-optic switches. These waveguide switches can be used to build time division multiplexers, which are devices that take pulse modulated signals from several input sources and integrate them into a single train of pulses to make efficient use of a fiber; it is necessary to use an optically controlled switch for this function because of the picosecond switching speeds required.

If such speed improvements could be achieved, there could result all-optical computers that are three orders of magnitude faster than current electronic machines, as well as parallel architecture machines. Such parallel processing of data would take greater advantage of the high information-carrying capacity of optical fibers, especially "multiplexed" data.

Simple indium gallium arsenide (InGaAs) photodiodes have excellent frequency response and perform well in 1.5 micron receivers that operate at multigigabit-per-second data rates.[26] However, they lack the internal gain needed to enhance receiver sensitivity for high-speed transmission over long distances. Early attempts to make InGaAsP avalanche photodiodes (APDs) were not successful because of the high dark current from tunneling and the degradation of frequency response from charge accumulation at heterojunction interfaces. Germanium APDs with low dark current and high gain have been developed and are now available commercially, but they contribute more excess noise than InGaAsP devices.

A device composed of layers of InGaAs, InGaAsP, and InP—known as the separate absorption, grading, multiplication (SAGM) avalanche photodiode—has worked well in experimental high-speed systems. With its gain-bandwidth product as high as 60 GHz, the SAGM APD is the best-performing photodetector for high-speed operation at 1.5 microns.[27]

Wideband, low-noise preamplifiers are as crucial as high-performance photodetectors for attaining high-sensitivity optical receivers. (A useful definition of receiver sensitivity in a digital repeater is the minimum input power required to achieve an error probability of 10^{-9}.) The sensitivity of an optical receiver is limited by the

[26]Tingye Li, "Advances in Lightwave Systems Research," pp. 5–18.
[27]Ibid.

quantum (or shot) noise associated with the primary photo-generated signal current in the detector. In practice, excess noise from the photodetector, thermal noise from the input circuit, device noise from the transistor preamplifier, and shot noise from leakage currents all contribute in varying degrees to prevent receiver performance from reaching the quantum-noise limit.

The best experimental APD receivers are about 5 dB more sensitive than the best experimental PIN receivers.[28] This sensitivity difference will increase to about 7 dB for production receivers because ultra-high-performance PIN photoreceivers are more difficult to manufacture. Further improvements in device performance may soon enhance the best sensitivities of APD receivers to a level about 15 dB above the quantum-noise limit. Additional improvements will likely require device breakthroughs that will provide considerably less excess noise from the APD.

Optical fiber sensors are beginning to emerge as competitive devices for performing tasks such as those required for aircraft engine and flight controls and for shipboard machinery and damage controls. These sensors have proved to be accurate and capable of operation in harsh environments contaminated with high electromagnetic interference (EMI), explosives, or corrosive gases. Fiber optic hydrophones, gyros, and magnetometers make up several of the high-performance sensor types. A number of hydrophones for evaluation purposes have been successfully tested at sea.[29] Two types of fiber optic magnetic sensors have been demonstrated,[30] one for high magnetic fields, the other for very small magnetic fields. Highly sensitive fiber optic gyros have also been fabricated in the laboratory, and they are expected to find universal usage because nearly all gyro applications have stringent space requirements.

The military is examining the use of fiber optic monitoring and control sensors and has actively pursued the development of several sensor types. Functions important in aircraft and ship controls include control of displacement, rotation, torque, and speed. The high EMI environment of military platforms that results from extensive radar and radio communication operations provides an excellent incentive for the development of

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[28]Ibid.

[29]Donald C. Shapero, *Photonics: Maintaining Competitiveness in the Information Era*, National Research Council, National Academy Press, Washington, D.C., 1988, p. 54.

[30]T. G. Giallorenzi et al., "Optical Fiber Sensor Technology," *IEEE Journal of Quantum Electronics*, Vol. QE-18, No. 4, 1982, pp. 626–665.

fiber optic position sensors. At present, both military and commercial companies are developing fly-by-light control systems.

ADVANTAGES AND DISADVANTAGES OF FIBER OPTICS

The advantages, from a military standpoint, of using optical fiber over conventional wire or coaxial cables include lighter weight, portability, ruggedness, low-loss transmission, large bandwidth, reduced need for shielding, high safety levels, and lower cost. Drawbacks to the military use of optical fiber include the potential for degradation of fiber in a nuclear environment, lack of ease of handling, maintenance and repair, and static fatigue or stress corrosion of the fibers. The advantages to using optical fibers far outweigh the drawbacks.

Despite the clear-cut gains in communication systems, however, the military services have been much slower than the commercial sector to capitalize on the potential fiber optic systems offer. This can be explained in part by the general lack of readily available hand tools, parts, training, and so forth for installation, maintenance, and repair of systems in the field. However, the situation is changing, due in part to the proliferation of commercial systems.[31]

Bandwidth of Light Transmission

The greatest attraction of fiber optics technology is the bandwidth of light transmission. According to theory, a carrier wave of high frequency can transmit meaningful information at a tremendous rate—the Nyquist theorem[32] sets a limit of one-half of the carrier's frequency for the fastest-changing signal a carrier wave can convey in a perfect medium.[33] Light in the visible and near-visible spectrum has characteristic frequencies in the range of 1,000 THz ($\sim 10^{15}$), roughly 100,000 times the frequency of microwaves.

The channel capacity of a transmission medium, or the maximum rate at which information may be transferred with negligible errors, is determined by communication

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[31]Victor C. Dawson and Peter L. Willson, *A Survey of Fiberoptics and Some Military Applications*, p. 3.

[32]F. Reif, *Fundamentals of Statistical and Thermal Physics*, McGraw-Hill, New York, 1965, p. 587.

[33]Richard S. Shuford, "An Introduction to Fiber Optics," *BYTE*, December 1984, p. 121.

theory. In a classic result due to Shannon,[34] the maximum error-free information transfer rate (in bits per second) achievable on a single channel increases directly with the bandwidth of the channel. Hence, the high bandwidth incurred as a result of high carrier wave frequency makes possible a vast amount of information transfer through a fiber optic link for a given signal-to-noise ratio.

As an illustration, a noise-free 1.55 micron wavelength carrier (a standard transmission wavelength) transmitting on a perfectly dispersionless fiber is theoretically capable of carrying hundreds of terabits ($>10^{14}$) of information per second. This is equivalent to 1.5 billion simultaneous telephone calls or 1.6 million TV channels on a *single fiber*.[35] Real transmitters and real fibers are, of course, limited by physical effects such as chromatic dispersion (which causes pulse broadening), refractive index profiles, and material properties. The highest data rates achieved to date are approximately 8 gigabits/sec (8×10^9), and the longest distance for coherent transmission is 290 km.[36]

Low Loss and Immunity to Electromagnetic Interference

Compared with metallic wire media, optical fibers have low loss. This is due to the difference in fundamental physical mechanisms between electronic and photonic systems. Losses in metallic wires arise from inherent resistance of the materials and from radiation losses, each of which can be explained by classical theories of charged particles (electrons in this case).[37] In contrast, although photons flowing in optical fibers experience the electronic equivalent of resistance losses, they do not suffer the radiation losses of electrons.

Because fibers are immune to interference from electric and magnetic fields, they can be installed in places where wires would require shielding. Because very little radiation escapes from the fiber cable to the environment, they may be tested for

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[34]C. Shannon and W. Weaver, *The Mathematical Theory of Communication*, University of Illinois Press, Urbana, 1949; Jacob D. Bekenstein, "Communication and Energy," *Physical Review A*, Vol. 37, No. 9, 1 May 1988, pp. 3437–3449.

[35]John E. Midwinter, *Optical Fibers for Transmission*, John Wiley & Sons, New York, 1979, pp. 400–401. The data rate for a single telephone channel is given as 64 kilobits/sec, and a multiplexing scheme used in the United States requires a data rate of 281 megabits/sec, for 4,032 channels. The number of multiplexed channels should be reduced by 20 percent to allow for extra bits to monitor the system operation.

[36]Tingye Li, "Advances in Lightwave Systems Research," pp. 5–18.

[37]John D. Jackson, *Classical Electrodynamics*, John Wiley and Sons, New York, 1975, pp. 210–213 and 391–394.

imperfections in highly accurate ways. Light or radiation in the long wavelength portion of the spectrum does not affect the transmission of data on fibers. Although leakage is extremely small from internal portions of the fiber to the external environment, neutrons and gamma radiation can damage the fiber; also, UV light can damage the coating used to protect the fiber.

Cost and Weight of Fibers

Depending on the thickness of the cladding used for the fibers, the weight of a single fiber is typically about 5 oz/km, while the cost is approximately $.30/m (or $300/km).[38] The transmission capacity of a fiber is roughly 15,000 times greater than a copper cable of the same size, while the weight of an optical fiber is about 120 times less than a copper cable of equivalent information-carrying capacity. The relative cost of transmitting information is lower for optical fiber than it is for copper cable, and roughly every three years, there has been a tenfold decrease in the cost per bit-kilometer.[39] It is believed that the cost of fiber will go down dramatically in the early 1990s when fiber optic devices become common household items.[40] This small size and weight relative to metallic wires makes the use of optical fibers attractive in applications where weight or space is a priority, such as in airframes or missile components.

Cost and Complexity of Electro-Optical Devices

Making use of all the bandwidth available with optical wavelengths requires complex interface equipment. The circuitry that forms the link between photonics and electronics must be of high quality to attain the efficient transfer of the signal and to compensate for the quirks that appear in any apparatus that blends two kinds of technology. The simplicity and economy of the fibers themselves are offset to some degree by the expense of this interface equipment.

The theoretical limits of information transfer via optical fiber are in the hundreds of terabits/sec range. However, real devices have limitations that restrict the rate of information transfer over the fibers. For example, Gallium Arsenide Field Effect

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[38] *Principles and Applications of Fiber-Optic Communication Systems*, Lightech, Inc., Richardson, Texas, 1985, p. 3–5.

[39] Robert J. Sanferrare, "Terrestrial Lightwave Systems," pp. 95–107.

[40] Private communications, Steven J. Anderson, Missile Systems Group, Hughes Aircraft Company, Canoga Park, Calif.

Transistors (GaAs FETs) have low amplification capabilities (gain) at frequencies beyond about 8 gigabits/sec, and Lithium Niobate modulated lasers are hard to drive at these frequencies.[41] Each new technology that increases the bandwidth-distance product eventually meets with some real limitation that restricts the utility of that device.

Properties of Optical Materials

To date, optical computing elements have not met with great success because of certain fundamental limitations inherent in the materials being used. These include the minimum size of a switching device, the minimum energy necessary to complete a switching event,[42] and material properties, such as nonlinearities in the refractive index, which are small. These fundamental limitations are measured in terms of several materials parameters,[43] including the optical quality and resistance to optical damage of the materials, switching response and recovery times, and the magnitude of the material nonlinearity, all of which have become the subject of intense study.

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[41] Paul S. Henry, "Lightwave Communications: Looking Ahead," briefing given to special committee of The National Research Council, 18 May 1988.

[42] There has been some controversy in recent years regarding the theoretical limit to the amount of energy necessary to complete a switching event. The limitation, according to classical theory in which noise depends upon the temperature, is some seven orders of magnitude below the currently achieved energy consumption of 0.1 picojoules/bit. There is some speculation, however, that computers that are completely reversible can be built—that is, that consume no energy, although they may take very long times to process information. See Rolf Landauer, "Dissipation and Noise Immunity in Computation and Communication," *Nature*, Vol. 335, 27 October 1988, pp. 779–784.

[43] A. M. Glass, "Materials for Optical Information Processing," pp. 657–662.

III. SOME MILITARY APPLICATIONS

INTRODUCTION

Contrary to tradition, the commercial sector has led in developing and applying fiber optics technology, while the military has had seemingly minor interest. The reason for commercial interest is clear; fiber optics offers great promise in communications. The military could benefit substantially by incorporating fiber optics into military communications with a relatively small investment because the technology has matured from the work that has been done by the commercial world.

The qualities of fiber optics make it the natural choice for military communications. Glass fiber is resistant to corrosion and electromagnetic interference (EMI) and therefore could continue to function even in a chemical or nuclear environment. In addition, because no electric fields are produced, the enemy cannot eavesdrop on communications.

In addition to communications, substantial benefit could be obtained from using this technology to perform military functions. The military is investigating the possibility of using fiber optics to improve many of its operations. The most promising applications are in weapon systems, surveillance systems, optical computing systems, and aboard vehicles. Table 1 presents some of the systems currently being developed that have the possibility of revolutionizing the field. The remainder of this section covers many proposed applications in these areas. However, this paper does not analyze the applications to consider their scientific and engineering feasibility.

COMMUNICATIONS

From a security viewpoint, the use of fiber optics for military communications is very well suited. Because no electro-magnetic fields are produced, eavesdropping is practically impossible. Therefore, it is very attractive for the military to use fiber for all types of communications (long, short, and local area).

The first nonencrypted communications security (COMM/SEC) system that the National Security Agency (NSA) has ever certified is now in production. The Intrusion Detection Optical Communications (IDOC) system is being built for the Air Force by

Table 1

MILITARY APPLICATIONS OF FIBER OPTICS

Application Category	System	Benefits of Fiber
Communications	Intrusion Detection Optical Communications (IDOC) System	Allows nonencrypted system EMI/EMP immunity Improved security
Weapons	FOG-M AAWS-M FOG-S PDAMS	EMI/RFI immunity High data rate Reduced vulnerability of launcher
Sensors Nuclear testing	High pressure sensor	Ability to sense in particle generation phase Ranges in excess of 10 kbar Accurate tracking of impulses
Image probes	Combustor flame probes	Compactness Reliability Ability to withstand high temperature
Surveillance Submarine	Ariadne Program	Ability to hold up in corrosive sea environment High sensitivity
UAV	R&D stage	Covert operation EMI/EMP immunity
Airborne Platform Avionics	Fly-by-light system	EMP/EMI immunity Weight/space savings
Radar	Phased array	Weight savings Capability to exploit parallelism of array
Aircraft stress monitoring	R&D stage	Light weight Small size Facilitation of maintenance Real-time monitoring

Table 1—continued

Application Category	System	Benefits of Fiber
Optical computing	Neural networks	Massive parallelism
Shipboard	Information system Damage control system (in tandem with sensor network)	Weight/space savings Low cost EMI/RFI immunity Ability to hold up in corrosive sea environment High data rate No spark hazard Ability to service live cable
Navigation	Fiber optic gyroscope (FOG)	Small size Light weight Low power Ruggedness Potentially modest cost Potentially great accuracy

Hughes Microelectronics Systems Division to link two computer systems or local area networks. This system can transmit data up to a rate of 12 megabits/sec, over distances up to 1.5 km.[1] The IDOC system, which transmits a guard signal, will automatically shut down if this signal is disrupted. Researchers at the Rome Air Development Center (RADC) at Hanscom Air Force Base are working to increase the system's capability so that 100 megabits/sec can be transmitted over 35 km.

A tactical version of this system is possible if fiber optic connectors could be made that are easy to set up and take down.[2] A fiber optic communications network could be installed, and the units in the field could simply "plug in" to the network to establish a secure ccmmunications link. It is also conceivable that the military could use fiber optics to fulfill the need for temporary short-range communications. Fiber could simply be spooled out on the ground by a couple of men to establish a temporary link. Another possible scenario would be to use a FOG-M type vehicle to transport a fiber optic cable

[1] "USAF Stresses Development of Semiconductor Laser," *Aviation Week and Space Technology*, 30 January 1989, pp. 57–58.

[2] Ibid.

over a distance. A group near the landing point could plug the fiber into a small modulator/demodulator, and a secure communications link would be set up.

WEAPON SYSTEMS

The only true fiber optic weapon system that is currently being developed is the FOG-M. The FOG-M is a medium range (~20–40 km), lock-on-after-launch weapon system to be used against helicopters and ground vehicles. The FOG-S, a fiber optic guided weapon, is also being proposed for the Navy. In addition, Hughes is proposing a fiber-guided weapon for the AAWS-M (Advanced Anti-armor Weapon System—Medium). This is a short range (~2 km)[3] man-portable weapon (~45 pounds), to be used primarily against tanks.[4]

Both the FOG-M/S and the Hughes AAWS-M concepts are hit-to-kill weapons and use a man in the loop for guidance. A fiber optic cable that is paid out from the missile during flight is used to transmit a picture back to the gunner from a camera (TV or IIR) in the nose of the missile. Guidance commands are also transmitted from the gunner's position to the missile through this fiber link. A typical optical fiber used in this weapon system is a single-mode fiber with a silica core doped with germanium or phosphorus, a pure silica cladding, and an ultraviolet clear polymer coating to protect the fiber from damage. The outside diameter of the fiber is 200–250 microns.

This weapon is made possible by the fiber optic data link. Copper cable lacks the bandwidth necessary to transmit a television picture from the camera in the missile to the CRT at the gunner's station. Therefore, in current man in the loop weapon systems (TOW & Dragon), the gunner must hold the cross hairs on the target until the missile impacts the target. Also, the range of current systems is short because copper cable is too heavy and occupies too much volume for a missile to carry a suitable length.

For a fiber-optic guided weapon to function, the fiber is required to pay out at missile velocities without breaking. Fiber payout speeds up to 600 ft/sec[5] [6] have been

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[3]Ezio Bonsignore, "Infantry Anti-tank Weapons: Where to Go," *Military Technology*, December 1987, pp. 35–50.

[4]James Vernon, "Military Taps Into Optical Fiber," *Defense Electronics*, June 1987.

[5]*Jane's Weapon Systems, 1988–1989*, Jane's Information Group, Inc., Alexandria, Virginia, p. 405.

[6]William Culver, CEO Optelecom, Gaithersburg, Maryland, claims that fiber has been paid out in laboratory tests up to speeds of 950 ft/sec.

successfully demonstrated in tests. The maximum theoretical payout speed is approximately 2,600 ft/sec.[7]

The FOG-M is being developed in the FAADS (Forward Area Air Defense System) program as the NLOS (Nonline of Sight) component to be used primarily against helicopters. However, the missile has a tandem-shaped charge warhead that will be used extensively as an "over the hill" tank killer. In a wartime environment, it is estimated that approximately 25 percent will be used against helicopters and 75 percent will be used against ground targets.[8]

Two launchers will probably be used: a HMMWV (high mobility multipurpose wheeled vehicle) carrying 6 missiles and the MLRS (multiple launch rocket system) launcher carrying 12 or 24 missiles. The first production lot is expected to consist of 16,000 missiles, of which about two-thirds will be TV guided and one third IIR guided. Because most of the expensive electronics are in the launcher, the cost of the missile is projected to be low. The approximate cost is $20,000 for the TV version and $60,000 for the IIR version.[9]

The Air Force and the Navy are also considering a fiber-guided weapon to be dispensed from an aircraft. In tests conducted at the Naval Weapons Research, Development, Testing, and Evaluation Facility at China Lake, California, A-7 Corsairs have launched fiber optic-guided weapons while in flight.[10] This missile would be very close, if not identical, to the current FOG-M concept. The primary difference would be the requirement of a second payout spool on the aircraft to realize the capability to launch the missile and then turn and fly in any direction (including opposite to the flight of the missile). This could be used as a surveillance unmanned air vehicle (UAV), as well as a weapon.

A possible tactical application of fiber optics technology is to use aircraft to drop buoys into the ocean with fiber optic-guided missiles. The buoys would have either a fiber optic or radio link to the aircraft or a radio link to a ship or land base. These

[7]Steve Anderson, Hughes Aircraft, Canoga Park, Calif., private communications.

[8]Richard Bergman, Chief of the Nonline of Sight (NLOS) Program at the Army Missile Command, private communications.

[9]Many diverse cost estimates exist and the cost of the missile will most likely be higher; Richard Bergman, Chief of the NLOS Program Office, projects a cost of $51,000 for the TV version and $69,000 for the IIR version. See David Harvey, "FOG-M: The Fiber-Optic Guided Missile," *Defense Science and Electronics*, May 1988, pp. 45–52.

[10]James Vernon, "Military Taps Into Optical Fiber," *Defense Electronics*.

missiles could be launched when an enemy ship or plane moves into their range. Queuing for this type of system could be radar, satellites, or aircraft. This technique could be used to deny both aircraft and ships to a fairly large section of ocean.[11]

Another possible weapon system is a bus and submunition combination using fiber optic links. The system that the Army is currently considering is the PDAMS. The PDAMS is a ballistic missile bus (much like the ATACMS—Army Tactical Missile System) carrying submunitions linked to the bus by fiber optic cables. The bus communicates with the launcher using a radio frequency link. The PDAMS system would be used to destroy tactical ballistic missiles (TBMs) within less than 5 minutes of the outbreak of hostilities. The objective of the system is to destroy the launchers before they are able to launch any missiles.[12]

The Army has adopted a follow-on-forces attack (FOFA) concept to counter the Warsaw Pact armor threat. The delivery vehicle generally accepted to carry out this mission is the Army Tactical Missile System (ATACMS)—an inertially guided bus. The possibility of using a delivery vehicle with a target recognition capability could provide substantial improvement over the current concept. A fiber optic-guided "cruise missile" type of bus delivering smart submunitions to the target location could fulfill this role. A preliminary analysis of the effectiveness of the smart bus has been conducted by an ongoing RAND study.[13]

SURVEILLANCE/SENSORS

Fiber optic sensors offer great promise in a variety of future sensing and surveillance applications because of their extremely rugged characteristics and ability to monitor a wide range of physical parameters. Table 2 lists currently measured performance parameters for some fiber optic sensors. As an example of a commercial application, the petroleum industry is currently using fiber optic pressure sensors inside oil wells because this type of sensor holds up well in that extremely hot and hostile environment.[14] In addition, the Defense Nuclear Agency (DNA) is sponsoring

[11]Steven Anderson, Hughes Aircraft, Canoga Park, Calif., private communications.

[12]William Culver, CEO Optelecom, Gaithersburg, Maryland, private communications.

[13]This work is being conducted in RAND's Arroyo Center, the U.S. Army's Federally Funded Research & Development Center.

[14]William Culver, CEO Optelecom, Gaithersburg, Maryland, private communications.

Table 2

FIBER OPTIC SENSORS AND PERFORMANCE PARAMETERS

Parameter of Interest	Measured Performance
Hydrophone (pressure)	20 dB—1 micropascal
Pressure	0-300 mm Hg ± 5% accuracy
Magnetic field	10^{-9} Gauss, 1mW optical power
Gyroscope (rotation)	10^{-3}°/h, 1mW optical power
Position (displacement)	10^{-3} in. resolution
Vibration (acceleration)	10^{-6}–10 g
Flow	10^{-6}–10^{-5} m/s
Liquid-level	0.5 mm
Oil pollution monitor	15 ppm
Temperature	0-100°C ± .001°C
pH	6.8-7.4 ± 0.01

development of pressure sensors for nuclear test instrumentation. Fiber optic pressure sensors appear to have ranges in excess of 10 kbar[15] and have been shown to be capable of accurately tracking pressure impulses (1 kbar in 1 ms).[16]

The use of fiber optics technology in battlefield surveillance has many possibilities. Fiber optic sensors lend themselves especially well to the battlefield

[15] B. Nelson and M. Gallagher, "High Pressure Fiber Optic Sensors for Nuclear Test Instrumentation," DNA 001–86-C-0194, 4 February 1987.

[16] Ibid.

environment because of their compactness, ruggedness, and extreme sensitivity to a variety of parameters. In Vietnam, remote sensors were used behind enemy lines. As an example of a military use, a pressure sensor buried in a road or a seismic sensor along the road could determine the number of vehicles that pass a point.

The high degree of sensitivity that could be obtained by using optical fiber to make an acoustic interferometer would vastly improve underwater submarine surveillance. In addition, the rugged nature of these sensors would substantially reduce maintenance and replacement costs due to the corrosive sea environment. Under the Ariadne Program, the Navy is currently developing an optical fiber underwater surveillance network.[17]

Pratt & Whitney is currently using advanced fiber optic sensors as image probes to study the flame patterns inside jet engine combustors.[18] In addition to image probes for engine research, fiber optic sensors could be used to monitor engine health during flight. Fiber sensors could monitor a number of engine parameters including temperatures, pressures, engine speed, and so on.

Another possible use of fiber optics for surveillance is unmanned air vehicles (UAVs) with a fiber optic data link between the vehicle and a ground station. The data link would be used to transmit guidance information to the vehicle and images (visual, infrared, or radar) from the vehicle to the ground station (much like the current FOG-M). In addition, fiber optic sensors could be placed on board the UAV and the output could be transmitted through the fiber to the ground station. The vehicle could also be used as a laser designator for a weapon such as Copperhead. The primary advantages of using a fiber optic link are immunity to jamming and EMI and covert operation.

OPTICAL COMPUTING

Fiber optics holds great promise in the field of computing. Several orders of magnitude increase in computational speed is conceivable over conventional computer architectures. One of the factors limiting the amount of information that can be transmitted in a conventional computer is that heat is produced when electrons travel through copper.[18] Optical computers would not have this problem.

[17]James Vernon, "Military Taps Into Optical Fiber," p. 23.

[18]"Commercial Labs Set Pace in U.S. Photonics Research," *Aviation Week and Space Technology*, 30 January 1989.

In order for optical computing to become a reality, a switching device is needed. A material with nonlinear optical qualities is necessary to construct such an optical switch. In 1986, David Miller (researcher, Bell Labs) developed the first photonic switching chip, the self electro-optic effect device (SEED). The SEED responds to light at certain wavelengths by changing its reflectivity. Bell Laboratories has just produced a 64×32 array of SEEDs.[19]

Several government research institutions are working on optical computing. The Naval Research Laboratory is concentrating on the possibility of developing parallel processing. DARPA (Defense Advanced Research Projects Agency) has also researched optical computing devices and has developed a switch with four inputs and four outputs. The Air Force is planning research at the Photonics Center at Griffiss Air Force Base.

Efforts are under way to produce a device that could automatically recognize a target using optical signal processing. This new system would use only phase information to recognize a target in real time. A phase-only filter was constructed at Lincoln Laboratories on fused quartz. This type of filter could be used in a wide range of wavelengths, including visible and infrared.[20]

A leading avenue for applying fiber optics technology to the field of computing is neural networks. Interest in neural networks has grown substantially over the past few years. Today, much research is being done in this field. Virtually every major defense contractor is pursuing research efforts in this new area.[21] The concept of neural networks, as the name implies, has its foundation in the structure of biological neurons. The manmade neural networks are composed of a variable resistor and a feedback loop to change the resistance depending on the output. Two features make neural networks different from other computer architectures: neural networks are trainable, and they are naturally massively parallel.[22]

The neural network is trained by letting it operate, test its output, and adjust the resistor accordingly. One way to accomplish this is to "teach" the network by having it "observe" a person perform a task. In this way, a neural network could learn to solve a

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[19]Ibid.

[20]"USAF Stresses Development of Semiconductor Laser," *Aviation Week and Space Technology*, 30 January 1989, pp. 57–58.

[21]Bruce D. Nordwall, "Industry, Defense Pursue Development of Learning, Adaptive Neurocomputers," *Aviation Week and Space Technology*, 14 November 1988, pp. 101–103.

[22]"DARPA Neural Network Study, October 1987-February 1988, Executive Summary," Lincoln Laboratory, MIT, Cambridge, Mass., 8 July 1988.

problem, relieving a programmer of the massive burden of specifying a step-by-step algorithm required by a conventional computer. A great deal of time and money could be saved if the software bottleneck could be eliminated. Some computer applications are too complex to be solved in the conventional manner. It is hoped that one neural network could learn to solve many different problems without the need for a person to program each individual application.

Unlike conventional computers, which have a central processing unit, neural networks use a large number of simple processing elements connected together. Therefore, neural networks are naturally massively parallel. As a result, a problem may be dissected into many subproblems and solved simultaneously. This allows a high-speed, fault-tolerant, computational system to be produced.[23]

Many computer applications lend themselves especially well to the use of neural networks:[24]

- target recognition
- word recognition
- sonar classification
- target tracking
- robotics.

Designing a neural network to accomplish these tasks would have a profound impact on current and future weapon systems. Examples of specific military tasks where neural networks could offer substantial improvement include the following:[25]

- detection of relocatable strategic weapons and recognition of ground features by means of satellite sensors
- stealth aircraft detection by infrared search-and-track systems.

Another application of fiber optics technology in the field of computing is optical storage devices. Dr. Donald W. Hanson, head of the Air Force's Photonics Center in the

[23]Ibid.
[24]Ibid.
[25]Bruce D. Nordwall, "Industry, Defense Pursue Development of Learning, Adaptive Neurocomputers."

Rome Air Development Center at Griffiss Air Force Base, said that because optical computers have the potential to run much faster than current electronic machines, "optical memory will be needed to support digital optical computing because the throughput rate of such computers will exceed the capacity of electronic memories."[26] An optical disksuitable for desktop computer applications could contain three orders of magnitude more data than a floppy disk.[27]

FIBER OPTICS ABOARD VEHICLES

The inherent advantages of fiber optics make it especially well suited for use aboard military and commercial vehicles. Ground, sea, and air vehicles could all benefit from the application of this technology. With the emphasis of aircraft design on lighter vehicles and the use of composites for fuel savings and radar absorption, fiber optics provides an avenue of great promise. Not only are the fibers much lighter than copper cable, but fibers are immune to EMI and lightning strikes, making electrical shielding unnecessary.

A GEC Avionics fly-by-light flight control system was successfully demonstrated on a lighter-than-air craft during late October 1988. A fiber optic cable transmits optical signals from the flight control computer in the gondola to the control surfaces at the ship's rear. Company representatives say that fiber optic path lengths are well suited for this application because of the flexing of the airship.[28]

According to Colonel Ted Wierzbonowski, director of phase III acquisition planning at the NASP (National Aerospace Plane) Joint Program Office, a great deal of fiber will be used aboard the National Aerospace Plane because of the need to reduce weight. Colonel Wierzbonowski believes that fiber optics technology is well advanced and that the task will be applying that technology to the NASP.[29]

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[26] "Commercial Labs Set Pace in U.S. Photonics Research," *Aviation Week and Space Technology*, 30 January 1989, pp. 60–61.

[27] "Researchers Foresee Sharp Increase in Military Photonics Applications," *Aviation Week and Space Technology*, 30 January 1989, pp. 56–57.

[28] "GEC Avionics Celebrates First Skyship 600 Fly-by-Light Flight," *Military Fiber Optic News*, 25 November 1988, p. 5.

[29] "A Lot of Fiber Optics Likely to Fly on NASP," *Military Fiber Optics News*, 9 December 1988, p. 3.

Incorporating fiber optics technology into transport aircraft can provide substantial benefits. Potential weight savings are 1,000 to 1,500 pounds for a large aircraft, if all the copper signal paths are converted to fiber.[30]

The use of optical fiber path lengths to link the radar elements of an airborne phased-array radar platform is very attractive because of the potential for enormous weight savings. An airborne conformal phased-array radar platform has thousands of active radar elements embedded in the skin of the aircraft. To take full advantage of fiber optics in phased-array radars, high-frequency waves must be transmitted in the fibers. Fiber optic cable could be used to connect the phased-array elements if high-modulation-rate lasers and modulators could be developed. These devices would be required to operate in the microwave and millimeter-wave frequencies used in the radar. Using fiber optic cables of different lengths to connect the phased-array elements and a central phase shifter would eliminate the need for an expensive electronics module at each element to provide phase shifting. Because only one phase shifter will be needed and a substantial length of copper cable will be replaced with fiber, the fiber optically converted system will be much lighter; this is of tremendous importance for an airborne radar platform. A breadboard phased-array radar antenna with four elements connected with fiber optic cables operating in the 2–3 Ghz range has been developed at Hanscom Air Force Base to demonstrate this concept.[31]

Fiber optic gyroscopes (FOGs) have the potential to revolutionize the navigation market, just as the ring-laser gyroscopes did 10 years ago. FOGs have several advantages over ring laser gyroscopes (such as small size, light weight, lower power requirements, ruggedness, and potentially modest cost) and currently have the potential to compete for low- and moderate-accuracy applications.[32] The Strategic Defense Initiative Organization (SDIO) is currently studying FOGs for use aboard a space-based interceptor. Litton is developing a three-axis inertial measurement unit that is projected to weigh less than a quarter of a pound and occupy a volume of approximately 1 cubic

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[30]Norris Lewis and Emery L. Moore, "Fiber Optic Systems for Mobile Platforms," *SPIE*, Vol. 840, 1987.

[31]"USAF Studies Linking Phased Array Radar With Fiber-Optic Cable," *Aviation Week and Space Technology*, 30 January 1989, pp. 61–63.

[32]Philip J. Klass, "Firms Research Fiber-Optic Gyros As Successors to Ring-Laser Systems," *Aviation Week & Space Technology*, 13 February 1989, pp. 79–85.

inch.[33] The same physical principal is used to design a FOG as is used to design a ring-laser gyroscope. The Sagnac Effect refers to the relative phase shift of two contra-rotating beams of light subjected to an angular rotation in the plane of the light beams. The phase shift is a direct result of the difference in path length that the two beams traverse. The accuracy of the Sagnac Effect is proportional to the optical path length. Because optical fiber could be used to achieve a very long path length in a small space by using a many-turn coil, interest in FOGs has been high.

Varo Incorporated is currently developing a fiber optic laser warning system for use aboard vehicles. This system will operate in the 400 to 1,000 nanometer wavelength range and will give 90 degrees of coverage.[34] The system will alert the operator when his vehicle is being illuminated by a laser. It is projected that this sensor will be used on air, sea, and ground vehicles, and that four to six sensors will be required for complete coverage.

The use of fiber signal paths is also very well suited for shipboard use. The extreme EMI levels, electrical problems, flooding, and corrosive environment make fiber natural choice for information transfer aboard ships. The use of fiber optics on vehicles for signal paths is attractive for the following reasons:[35]

Security: No electromagnetic fields are produced, eliminating the possibility of eavesdropping. Copper cable needs a conduit to eliminate this problem, enhancing the weight savings of fiber.

Ruggedness: Fiber is immune to short circuits and is resistant to chemical and nuclear effects. Fiber can also be run in damp and highly corrosive environments.

Maintenance: Because the fiber carries no current, live cable may be serviced.

Installation: Because fibers do not produce heat or sparks, cable can be run in small, closed areas (including ammunition magazines or fuel

[33] Ibid.

[34] *Jane's Weapon Systems, 1988–1989*, Jane's Information Group Inc., Alexandria, Virginia, p. 865.

[35] W. R. Little, D. C. Otto, and C. A. Denier, "A New Approach to Sensors for Shipboard Use," *SPIE*, Vol. 840, 1987.

points),[36] with no special provisions for fire or explosion hazards.

In 1982, the U.S. Navy introduced fiber optics technology into an AEGIS cruiser. A fiber optic damage control system was developed. Amplitude-type fiber optic sensors were used to detect smoke, liquids, temperature, and rate of temperature change for monitoring fire and flooding situations.[37]

A new and very exciting concept under development is embedding optical fiber sensors within the vehicle structure for "health monitoring." The Air Force is currently sponsoring a project to define the requirements for such structures, develop a baseline architecture, determine possible technology gaps, demonstrate the concept, and evaluate the feasibility of its development.[38] This embedded sensor structure could be used during flight to monitor structural integrity and flight loads of the vehicle so that the flight crew could be notified of a problem or a central computer could, possibly, initiate automatic corrective action. This sensor network could also be used after flights to alert maintenance teams of problems or of the need for repairs. This type of sensor network within the aircraft structure could be of great comfort to those who are concerned about the structural integrity of an aging transport fleet, whose fears have been exacerbated by the preponderance of failures aboard commercial aircraft in recent history. This type of fiber "nervous system" for vehicles has great promise for the future, because much emphasis is being placed on using composites as part of the load-carrying structure. One very strong argument against the use of composites for this function is that, in many cases, composites suffer catastrophic failure with little or no prior evidence. This monitoring system may alleviate that concern by providing warning of possible failure.

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[36]James Vernon, "Military Taps Into Optical Fiber," *Defense Electronics*, June 1987.

[37]R. A. Johnston and R. C. Stewart, "Implementation of Fiber Optics in U.S. Naval Combatants," *SPIE*, Vol. 840, 1987.

[38]"Fiber 'Nervous Systems' For Lifetime Monitoring of Aerospace Vehicles," *Military Fiber Optic News*, 27 January 1989, p. 3.

IV. TRENDS

FIBERS

The two main characteristics of a fiber waveguide are its attenuation and bandwidth. Attenuation in present silica materials has been reduced to almost the theoretical lower limit[1] by reducing the absorbing impurity levels to below 1 part per billion.[2] The fundamental or theoretical minimum loss parameter in fused silica is approximately 0.1 dB/km at a wavelength of 1.55 μmeters, and values of 0.16 dB/km have been demonstrated in the laboratory.[3] Research is currently under way to fabricate fibers using fluoride glasses, which may have attenuations 10 to 100 times lower than present fibers. There are, however, enormous problems to overcome in making practical fiber waveguides from these new materials, because the very properties that produce low attenuation in fibers also account for poor physical, chemical, and structural behavior.[4] Fibers containing fluorides, for example, are attacked by moisture, have a tendency to crystallize, and have a mechanical strength about one-tenth that of fused silica fibers.[5] The research warrants continuation, however, because the benefits are so great. Transoceanic cables without repeaters are an example of a potential benefit that these ultralow-loss fibers would make possible.

The maximum data rate (which is directly related to the bandwidth) of an optical signal that can be supported in a fiber is presently limited by fiber material and waveguide dispersion, interacting with the spectral width of the optical sources. Current off-the-shelf fibers can transmit data at 3.4 gigabits/sec, and fiber tested in the laboratory

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[1]When the density of impurities is very small, attenuation due to light scattering from these impurities follows a λ^{-4} law known as Rayleigh scattering.

[2]A. M. Glass, "Optical Materials," *Science*, Vol. 235, 27 February 1987, pp. 1003–1009.

[3]Ibid.

[4]Martin G. Drexhage and Cornelius T. Moynihan, "Infrared Optical Fibers," *Scientific American*, Vol. 259, November 1988, pp. 110–116.

[5]A. M. Glass, "Optical Materials."

has been shown to transmit data at up to 16 gigabits/sec.[6] With emerging-single frequency sources,[7]

however, this shows no sign of becoming a limiting factor. Further, tailored waveguide designs have been used to make fibers that can provide for flexibility in the choice of light source.[8] This fiber design work is an important research effort that should proceed simultaneously with other activities to facilitate alternative system designs.

In addition to attenuation and bandwidth, several environmental requirements define fiber degradation in use. These requirements have become increasingly important, especially in military applications, as the desire has evolved both to reduce fiber protection and to submit fibers to more hostile environments. This has led to complex materials studies aimed at the improvement of materials properties.[9] One such effort involves studies of atomic defects generated (or activated) by hydrogen diffusion into the glass (typically from water), leading to optical absorption at system wavelengths being used. While this phenomenon is generally understood and empirical results show that the attenuation increase is usually negligible, there remains concern about adverse environments with high hydrogen content or high temperature. Continuing research to understand this problem at a fundamental level could help reassure fiber users and assist manufacturers in expanding the environmental durability.

A second area that has attracted the effort of materials scientists and is of particular concern to the military, especially in their use of fiber for fiber-guided weapons, is hermetic coatings to improve the tensile strength of fibers. Progress has been adequate in this area and continues as higher specific strength materials become available.

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[6]"Researchers Foresee Sharp Increase in Military Photonics Applications," *Aviation Week and Space Technology*, 30 January 1989, pp. 56–57.

[7]Note that there can never be a true *single* frequency source, but the linewidth or the spread in the source can be reduced to very small values.

[8]Dispersion-shifted or dispersion-flattened fibers have been designed that allow the spreading of a light pulse due to fiber material dispersion to cancel the spreading due to spectral bandwidth of the laser.

[9]*Photonics: Maintaining the Competitiveness in the Information Era*, National Research Council, National Academy Press, Washington, D.C., 1988.

LASERS

A key element of all long-haul optical communication systems—more so than in other areas of application—is the semiconductor laser. The desirable characteristics of the semiconductor laser are determined in large measure by the characteristics of the optical fiber and the lightwave system architecture. Future lightwave systems are likely to contain a large number of closely spaced channels operating in the 1.5 to 1.6 micron wavelength band of low loss. In addition, high bit rate systems (greater than 1 gigabit/sec) require narrow-line, single-frequency lasers to offset the chromatic (material) dispersion of the fiber.

As noted earlier, two types of lasers have been extensively investigated for obtaining single-wavelength emission: the external cavity laser and the distributed feedback laser. The linewidth of a semiconductor laser is determined by the fluctuations in the phase and intensity of the photon field in the laser cavity, which in turn depend on the cavity length. Continuous wave linewidths on the order of a few kilohertz (which is necessary for coherent applications) have been obtained for external cavity lasers, compared to those of many megahertz for distributed feedback lasers.

An important problem is the behavior of lasers under modulation conditions. A spontaneous change in frequency of the laser under direct modulation during a pulse interval, known as "chirping," is an important limitation as one goes beyond about 2 gigabits/sec. The chirping behavior of semiconductor lasers is determined in part by the internal structure of the laser. Buried heterostructure lasers have generally low chirp and are favored for high bit rate systems—despite their complexity in manufacture. These types of lasers have been fabricated and operated at high temperatures (130° C), at high bit rates (>3.4 gigabits/sec), at high powers (100 mW near room temperature), and with lifetimes in excess of 50 years at 25° C.[10]

As systems with capabilities beyond 10 gigabits/sec become possible, it is likely that external modulation will be necessary for high bit rate, error-free transmission. However, this results in additional power loss, and the system designers would need high power (greater than 50 mW) lasers for practical high bit rate systems.

In terms of military research and development, Rome Air Development Center (RADC) is trying to develop semiconductor lasers that operate at different wavelengths

[10]Tingye Li, "Advances in Lightwave Systems Research," *AT&T Technical Journal*, Vol. 66, No. 1, January/February 1987.

from those used in the telecommunications industry (typically 1.3 and 1.55 microns). The goal of the RADC research is to develop "solid state lasers that can be modulated faster, have much lower power requirements, and can be made into arrays." Dr. Andrew C. Yang, retired chief of RADC Electro-optics Device Technology Division, believes that the semiconductor laser is "the one enabling technology that would make it possible to think about photonics in a real sense."[11]

The highest reported continuous wave power achieved from a single emitter diode laser is in the range of 200 to 250 mW.[12] By spreading out this power through the use of a multi-emitter array, the power output can be increased substantially. A 10-emitter array has been used to generate continuous wave power of 1.5 W, and a 100-emitter array has generated 5.4 W.[13] Such advances have made possible applications such as fiber optic power transmission and satellite optical communications that were unattainable only a few years ago.

CONTROL DEVICES

Photonic Switches

A number of technologies have been demonstrated for switching an optical signal between two or more outgoing paths. These include mechanical devices that physically move fibers or that physically move lenses or mirrors directing an optical beam; optoelectronic devices, typically fabricated from lithium niobate ($LiNbO_3$), where an applied voltage across two or more electrodes causes a field within an electro-optic material, which in turn changes the coupling of waveguides within the material or otherwise modifies the optical characteristics of an optical circuit within the material; electrically, optically, or acoustically controlled gratings created within a material to cause diffraction of an optical beam; and electrically or optically controlled nonlinear optical devices.

Of the variety of optical switching devices demonstrated or proposed, some are more practical than others, and some have near-term applications. However, optical

[11]"USAF Stresses Development of Semiconductor Laser," *Aviation Week and Space Technology*, 30 January 1989, pp. 57–58.

[12]Peter S. Cross et al., "Ultrahigh-Power Semiconductor Diode Laser Arrays," *Science*, Vol. 237, 11 September 1987, pp. 1305–1309.

[13]Ibid.

switching devices are in general larger and more power consuming than their electronic counterparts, and many of these devices have numerous practical limitations, such as temperature sensitivity, polarization dependence, wavelength dependence, requirements for high voltages, and high loss.[14] Improvements in materials and the design of these devices are the two key dimensions of current research. In addition, much systems research is also needed to achieve large-scale application of optical switching devices as replacements for electronic switching devices.

Optical Amplifiers

Optical amplifiers are potentially important building blocks of all optical information systems. In current optical communication systems, the amplification function is accomplished by converting the optical signal to electronic form (by a photodetector), amplifying the electronic signal with an electronic amplifier, and then reconverting the amplified electronic signal to optical form. There are two main types of optical amplifiers: fiber-based amplifiers and semiconductor laser-based amplifiers.

The main uses of optical amplifiers are in pre-amplifier applications (where amplification of low-level signals is performed and there is no intentional loss between the output of the amplifier and the receiver) and in in-line applications (where relatively large optical signals are amplified and loss is expected between the output of the amplifier and the receiver). The former are likely to be important in high bit rate (>2 gigabits/sec) systems: the latter are believed to be useful in long haul (as compensators for fiber losses), in the local loop, and in optical switching to compensate for losses in the switches. To date, no practical semiconductor laser amplifier has been developed.[15]

Fiber amplifiers suffer from the high pump power required for amplification. Research needs to be performed on special fibers with low loss as well as special dopants for optically pumped fiber amplifiers.

Photodetectors

The positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD) are the most commonly used photodetectors for the detection of optical signals in

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[14] *Photonics: Maintaining the Competitiveness in the Information Era*, National Research Council, National Academy Press, Washington, D.C., 1988.

[15] Ibid.

lightwave systems.[16] Lightwave systems operating in the 1.3–1.6 micron region use both PIN photodiodes and APDs. However, for high bit rate (>2 gigabits/sec), high performance, and communication applications, avalanche photodiodes are the detectors of choice because the electrical signal generated in the APD is internally amplified, allowing lower levels of optical signal to be detected than the PIN photodiode.[17]

Photodetectors currently in development are based on the indium phosphorus/indium gallium arsenide (InP/InGaAs) material system and are of the heterojunction type,[18] separate light absorption region and a separate current multiplication region. A particular type of APD device fabricated from these materials, called the separate absorption, grading, multiplication (SAGM) APD, has exceptional response speed and high sensitivity. For example, with a receiver operating at 8 gigabits/sec, at a wavelength of 1.5 microns, a sensitivity of –26 dBm has been obtained for a SAGM APD with a 10^{-10} bit error rate.[19] Typical avalanche photodiodes of this type yield receiver sensitivities that are 5 to 10 dB better than those achieved with positive-intrinsic-negative (PIN) detectors.

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[16] Richard W. Dixon and Niloy K. Dutta, "Lightwave Device Technology," *AT&T Technical Journal*, Vol. 66, No. 1, January/February 1987, pp. 73–83.

[17] *Photonics: Maintaining the Competitiveness in the Information Era.*

[18] A heterojunction is a structure that consists of several layers of a compound, each with varying compositions.

[19] Richard W. Dixon and Niloy K. Dutta, "Lightwave Device Technology."

Appendix A

TECHNICAL BACKGROUND INFORMATION

FIBERS: BASIC THEORY AND DEFINITIONS

Fibers as Optical Waveguides

Light (or, more generally, an electromagnetic wave) travels with a constant speed of 299,792,458 m/sec (approximately 1 ft/nanosec) in free space. When light travels through a more dense media, such as glass, the speed of propagation decreases. The speed of light in free space divided by the speed of light in a given medium yields a number that is termed the index of refraction. Clearly, the higher the index of refraction of a material, the slower light travels through that material. Table A.1 presents the index of refraction for some typical materials.

This slowing down of light as it travels through a more dense medium gives rise to refraction, or the bending of light. When light passes through a material of one index of

Table A.1

INDEX OF REFRACTION FOR SOME TYPICAL MATERIALS

Material	Index of Refraction
Air	1.0003
Diamond	2.42
Glass, light barium flint	1.58
Glass, zinc crown	1.52
Polyethylene	1.52
Fused quartz	1.46
Corning glass single mode fiber	1.468
Water	1.33

SOURCE: D. Halliday and R. Resnick, *Fundamentals of Physics*, John Wiley and Sons, New York, 1970, p. 670.

refraction into a material with a different index of refraction, the path of the light bends in accordance with Snell's law:

$$n_1 \mathrm{SIN}(\theta_1) = n_2 \mathrm{SIN}(\theta_2)$$

where n_1 is the index of refraction of the first material, θ_1 is the angle between the path of the light in the material and the normal to the surface, n_2 is the index of refraction of the second material, and θ_2 is the corresponding angle in the second material. Thus, if light passes from a less dense medium to a more dense medium ($n_1 < n_2$), the light bends toward the normal in the second material.

Since the bending angle is greater in the less dense material, it is possible for the bending to reach 90 degrees in the less dense material when the angle of incidence in the more dense material is something less than 90 degrees. That is, light that travels from a more dense material to a less dense material can be totally reflected at the surface if the incident angle is sufficiently large. The angle where this occurs is called the critical angle, or Brewster's angle. Using Snell's law, the critical angle can be written as

$$\theta_1 = \mathrm{ARCSIN}(n_2/n_1)$$

where $n_2 < n_1$.

This property is used in optical fibers to keep the light from leaking to the environment. An optical fiber or waveguide may be considered a cylinder, with a central core region having a refractive index n_1 surrounded by a cladding region having a refractive index n_2, where the refractive index of the core is generally greater than the refractive index of the cladding.[1] Transmission along this structure can be thought of in terms of total reflection at the boundary between these two regions. For example, an optical fiber with core index of refraction $n_1 = 1.468$ and external cladding index of refraction $n_2 = 1.44$ has a critical angle or total internal reflection angle of 78.8 degrees. The optical power is carried through modes or electromagnetic field distributions, which satisfy the well-known equations for electromagnetic phenomena called Maxwell's equations.

Similarly, if light is introduced into a coated fiber from a medium (say, air) whose index of refraction is n_0 there is a maximum angle for which that light will be propagated

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[1]P. L. Bocko and J. R. Gannon, Corning Glass Works Technical Report *TR-21, August 1983*. Note that not all fibers have $n_1 > n_2$; the Japanese are investigating an optical fiber, dubbed z-fiber, that has $n_1 < n_2$.

wholly within the core of the fiber. The sine of this angle is called the numerical aperture; it is defined in terms of the respective indices of refraction as

$$\mathrm{SIN}(\theta_{NA}) = (n_1/n_0)\mathrm{COS}(\theta_c) = (1/n_0)(n_1^2 - n_2^2)^{1/2}$$

Using the indices of refraction for a typical fiber— $n_1 = 1.468$, cladding material, $n_2 = 1.44$, and air, $n_0 = 1.0003$—the numerical aperture is calculated to be $\mathrm{SIN}(\theta_{NA}) = 0.285$ or $\theta_{NA} = 16.6$ degrees. Hence, for a fiber with core and cladding indices of refraction as used in this example, any light introduced into the fiber within a cone of 16.6 degrees will travel entirely within the core of the fiber.

Fiber Cladding Profiles

Optical fiber waveguides are made in two major classifications, one of which is subdivided into two varieties. The major division is between fibers that convey light in single or multiple modes, where a mode can be thought of as a group of rays bouncing through the waveguide at a given angle of incidence. The multimode fibers are differentiated by the profile of the refraction index across the fiber's diameter.

Hence, the three kinds of fibers are, in the order in which they were produced historically, step index multimode fiber, graded index multimode fiber, and single-mode fiber. The step index multimode fiber features an abrupt transition of indices of refraction between the core and cladding. Although this type of fiber is easy to manufacture, it typically has a low bandwidth (10 MHz/1 km). Graded index multimode fiber exhibits an index of refraction that reaches a peak in the center of the core and gradually tapers off to a constant (lower) value in the cladding. This type of fiber is more difficult to manufacture, but with a careful design of the core, bandwidths as much as 200 times greater than step index multimode fiber can be achieved (2 GHz/1 km). Finally, single-mode fiber has a step index profile, but it is distinguished by its much smaller core size and by a smaller difference in index between the core and the cladding. This fiber requires a relatively high degree of precision manufacturing because of the very small core dimensions, although very high bandwidths can be achieved (30 to 50 GHz/1 km are common).

Information-carrying Capacity and Fiber Bandwidth

Information transmission capacity is specified by bandwidth in many traditional transmission media. The signal is transmitted on a carrier frequency, and the bandwidth is the limit of the modulating frequency superimposed on that carrier frequency, or on the range of carrier frequencies that can be transmitted.

The bandwidth is defined technically as the lowest modulation frequency at which the ratio of output to input optical power decreases to a fraction (usually one-half) of the zero frequency value. Since the bandwidth of an optical waveguide is approximately inverse to its length (physically, this is due to mode mixing, or light from different modes of the same signal interfering with one another), the bandwidth-length product is often quoted as a quality characteristic.

In optical waveguides, the carrier frequency essentially is determined by the wavelength of light. This light carries digital signals that can be transmitted at a particular bit rate. The bit rate at which these digital signals can be received cleanly is related to the bandwidth of a fiber optic system. Although multimode fibers are specified in terms of bandwidth, in single-mode fibers, bandwidth is replaced by a term known as pulse dispersion.

Loss and Dispersion

Power losses in fibers are of two general types. First, material losses arise from the fact that both the core and the cladding are real materials that differ slightly from our ideal models. Second, fiber design losses are incurred from joins, splices, and at light insertion, as well as scattering losses induced by any variations in core-cladding interface radius or in core-cladding refractive index differences.[2] Further, such losses can arise from finite cladding thickness (that is, at the cladding-jacket boundary, since some mode energy necessarily propagates within the cladding), and from any deviations of the fiber from linearity (bending losses).

The material parameters of importance are scattering loss, absorption loss, and dispersion. Absorption loss has been effectively eliminated in silica fiber materials at transmission frequencies of 1.3 and 1.55 microns by reducing the impurities that cause the absorption to levels below 1 part per billion.[3] Real losses in fibers are now essentially

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[2]M. E. Lines, "The Search for Very Low Loss Fiber-Optic Materials," *Science*, Vol. 226, 9 November 1984, pp. 663–668.

[3]A. M. Glass, "Optical Materials," *Science*, Vol. 235, 27 February 1987, pp. 1003–1009.

limited by scattering from the random density fluctuations in the glass (called Rayleigh scattering). This fundamental loss parameter is about 0.1 dB/km in fused silica at a wavelength of about 1.55 microns. To achieve losses below this, other material systems such as chlorides and fluorides or even modified silicates containing alkali metals and aluminate modifiers are being considered.[4]

Material or chromatic dispersion is also another critical parameter for optical fiber technology. Since all real sources, even laser sources have a finite spectral width, an optical pulse injected into the fiber is broadened by the dispersion during propagation, eventually leading to pulse overlap and errors in pulse discrimination. The effects of dispersion can be minimized by using narrow linewidth lasers or by designing the fiber to allow material dispersion to cancel waveguide dispersion, called dispersion-shifted fibers.

Chromatic dispersion is determined by the fiber's material composition, structure and design, and operating wavelength. It is measured in terms of picoseconds of light pulse "spread" per nanometer of laser spectral linewidth per kilometer of fiber length. (The units of chromatic dispersion are psec/nm × km.)

The conversion from dispersion to bandwidth can be approximated by the following formula:[5]

$$\text{Bandwidth} \times 0.187/[(\text{Dispersion}) \times (\text{Linewidth}) \times (\text{Length})]$$

where dispersion is a physical property of the fiber, the linewidth refers to imperfections in the laser, and length also refers to the fiber. As an example, Corning single-mode fiber (designated CPC3) has a dispersion of 17.6 ps/nm × km, a typical laser linewidth is 2 nm, and the bandwidth for a 100 km length of this fiber is 53 MHz.

Tensile Strength

The basic difference between the strength of copper and glass is due to the different behavior of the two materials in their stressed state. Copper is a ductile metal, while glass is considered a brittle material. Two phenomena dominate brittle material failure: fast fracture and fatigue degradation. Although the failure mechanism is identical, the time to failure is different. This failure mechanism depends on the surface flaws, since unflawed glass exhibits very high strength—on the order of 1 to 2 million

[4]Ibid.

[5]Craig M. Lemrow and Paul R. Reitz, "Single Mode Optical Waveguide Specifications," *Telecommunications Magazine*, Vol. 18, No. 5, May 1984, pp. 76–78.

psi. The randomness inherent in flaws imparts a probabilistic distribution to the tensile strength of fibers. Therefore, in the manufacture of optical fibers, abrasion protection coatings are of the utmost importance in preserving fiber strength.

Cost

The price of multimode, graded-index-fiber cable dropped during the late 1970s because of the increase in quantities sold as well as significant improvements in manufacturing yield. Single-mode fiber also decreased in cost, but at a more gradual rate until some large purchases along with significant increase in yield caused the price to drop rapidly. Today, single-mode fiber cable is equal to or less than the cost of multimode cable, currently running at about $.30/m. However, a reduction is expected in the 1992 timeframe when fiber optics are introduced into the home and economies of scale take over.

TRANSMISSION AND CONVERSION DEVICES

The current limitation to the replacement of electronic systems with fully photonic systems is in the devices that perform control functions such as switching, modulation, and amplification. Present optical/photonic control devices are operated either mechanically or electronically and hence are limited by their speed, power requirements, and amount of data they can process. That is, properly processing and routing signals through a system requires that the photonic signals be converted to electronic signals, then amplified and regenerated in noise-free form, unraveled (a process known as demultiplexing), processed, mixed (or multiplexed), and recombined into pulses of photons. It is by far preferable to perform these operations using light alone, because optical devices are capable of about three orders of magnitude faster switching speeds, consume up to an order of magnitude less power per switching event, and have the potential to handle many signals in parallel. In addition, optically operated devices will be far less susceptible to electromagnetic interference than their electronic counterparts.

Sources and Transmitters

All optical sources produce light output that contains energy at a number of wavelengths around a central wavelength. For example, a typical 1.3 micron laser has an optical output centered at 1.3 microns but contains some lower-level energy at

efficient light emitter because it has an indirect band gap.[6] In addition, it is not useful for nonlinear optics because it has a center of symmetry. The first semiconductor laser ever fabricated was made from gallium arsenide (GaAs), which efficiently emits light near 0.88 microns (near infrared). However, since the optical loss of fibers carrying light of 1.5 micron wavelength is some one-tenth of that at 0.88 micron wavelength, it is necessary to use indium phosphorus-gallium arsenide (InP-GaAs) alloys operating at longer wavelengths for long-distance transmission. These alloys form devices that emit light in the 1.3 to 1.55 micron region of the spectrum, while the longest wavelength for a device that can be grown on InP is about 1.7 microns.

Great improvements have been made in the power and efficiency achievable at room temperature from these small sources of optical energy. For example, continuous wave power in excess of 5 W has been demonstrated with a monolithic array of 100 emitters,[7] which is more than 1,000 times more powerful than the lasers in compact disk players. In addition, more than 100 W with 50 percent power conversion efficiency was obtained in 150 microsec pulses from a monolithic linear array of 1,000 lasers. Such arrays have been prepared in a two-dimensional configuration to achieve a quasicontinuous wave power density in excess of 3 kW/cm^2 at a wavelength of about 0.81 microns.[8]

Photodetectors

The photodetector is an important component in any lightwave transmission system. Lightwave receivers use high-speed photodetectors for conversion of the incoming light pulses to electrical pulses. The photodetector transforms the input (or received) optical signal into an electrical signal, from which the original coded information is retrieved using a series of functions including amplification, equalization, filtering, and timing. Photodetectors are also used for monitoring the power output of the source at the transmitter and maintaining it within a specified range through a feedback circuit.

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[6] A. M. Glass, "Optical Materials," *Science*, Vol. 235, 27 February 1987, pp. 1003–1009.

[7] G. L. Harnagel et al., *Electronics Letters*, Vol. 22, 1986, p. 605.

[8] P. S. Cross et al., "Ultrahigh Power Semiconductor Diode Laser Arrays," *Science*, Vol. 237, September 1987, pp. 1305–1309.

The positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD) are the most commonly used photodetectors for the detection of optical signals in lightwave systems. The electrical signal generated in the APD is internally amplified, which makes it capable of detecting lower levels of optical signals than the PIN photodiode. The minimum detectable signal for both PIN photodiodes and APDs is determined by internally generated electrical noise. For PIN photodiodes, the principal source of noise is "shot noise," which arises from small, randomly varying thermally generated currents. For APDs, the principal source of noise is the probabilistic avalanche process, whereby a pair of photogenerated carriers undergo multiplication. This process also results in signal amplification.

Because total noise increases with increasing bandwidth, the minimum detectable signal for both PIN photodiodes and APDs increases with increasing data rate. The APD can detect lower signal levels than the PIN photodiode.

The PIN photodiodes are easier to fabricate and operate and are extensively used for low and moderate data rate lightwave transmission systems. Higher sensitivity APDs are advantageous in applications in which extreme regenerator spacings or higher data rates are desired.

FUTURE OPTOELECTRONIC DEVICES

Research and development of discrete sources and detectors has improved the performance and lowered the cost of optical information transmission systems. The regenerator devices in these systems are hybrid circuits in which the electronic functions use silicon technology, while the photonic functions use gallium arsenide (GaAs) or indium phosphide (InP). Exploratory work in devices is currently being done in the following areas:

- development of devices for new architectures such as interconnection between computers, parallel data transfer, or coherent detection systems
- monolithic (single-chip) integration of sources, detectors, amplifiers, and timing circuits leading to a single-chip regenerator

The monolithic integration of electronic and optical elements is still in the early stages of investigation, although some simple integrated transmitter and receiver circuits

have already been fabricated. A key element in optoelectronic integrated circuit technology is the development of the materials growth technology, in which vapor-phase epitaxy is expected to be most useful.

Optoelectronic integration is driven by the desire to lower cost, improve performance, and increase functionality compared to discrete component technology. Integrated technology will reach its full potential only after lightwave materials and processing technologies are more fully developed and the need for larger volumes of devices is established.

GLOSSARY

Absorption loss: Phenomenon in which light energy propagating in a fiber is absorbed by the fiber as heat. The main mechanisms of absorption are atomic defects introduced in the manufacturing process, impurities in the material, especially metal and hydroxyl ions, and intrinsic absorption from molecular transition bands.

Attenuation: Losses in signal that occur in a waveguide because of material imperfections. Major causes of attentuation are scattering, absorption, and micro- and macrobending.

Avalanche photodiode (APD): A photodiode that has an internal gain greater than one. This gain is provided when the electrons created by the impingement of photons have sufficient kinetic energy to create additional electron-hole pairs through collisions. This is accomplished by achieving a sufficiently large reverse bias across the p-n junction.

Cladding: The dielectric material that surrounds the core of an optical waveguide. By using a cladding material with a lower index of refraction than the core, total internal reflection of the light wave occurs at the core-cladding interface.

Coherence length: The distance over which a propagating light beam may be considered coherent. If light of central wavelength λ and linewidth $\Delta\lambda$ traveling in a medium of refractive index n, the coherence length is approximately $\lambda^2/n\,\lambda$.

Coherent light: Electromagnetic wave trains that propagate in phase with one another.

Core: The central region of an optical waveguide through which light is transmitted.

Degree of coherence: A measure of the coherence of a light source, which depends on measurements made in a two beam interference experiment. Light is considered highly coherent when the degree of coherence is greater than 0.88, partially coherent for values slightly less than 0.88, and incoherent for small values.

Dispersion loss: Signal distortion caused by pulse spreading, which limits the information-carrying capacity of a fiber. Dispersion may be of two basic types, modal (intermodal) or intramodal.

Electro-optic effect: A change in the refractive index of a material resulting from the application of an electric field.

Fiber bandwidth: The frequency at which the magnitude of the transfer function of an optical waveguide has fallen to half the zero frequency value, that is, the frequency at which the signal attentuation has increased by 3 dB. Because the bandwidth of an optical waveguide is approximately reciprocal to its length (primarily because of mode mixing in multimode fiber and dispersion spreading in single-mode fiber), the bandwidth-length product is often quoted as a quality characteristic.

Field effect translstor (FET): A transistor that uses an electric field applied across two regions to produce a device of high sensitivity.

Fresnel reflection: The reflection of a portion of light incident on the interface between two homogeneous materials having different refractive indexes. For light injected into the end of a fiber, this accounts for a loss of approximately 4 percent of the total optical power of the source.

Fundamental mode: The lowest order mode of propagation of a waveguide. Single-mode fibers are designed to propagate only this mode.

Fused quartz: Glass made by melting natural quartz crystals. Also called fused silica or fused silica glass.

Gap loss: The loss of optical power caused by a space between axially aligned fibers.

Graded index fiber: An optical fiber that has a core with a refractive index that varies with the radius from a maximum value at the center of the core to a minimum value at the core-cladding interface. This type of fiber is used to reduce dispersion in multimode fibers.

Index of refraction: The ratio of the velocity of light in a vacuum to that in a given medium. Also called the refractive index.

Interference: In wave propagation (including light), the interaction of two (or more) waves to add or reinforce (constructive interference) or subtract or cancel (destructive interference). For two waves of the same wavelength, this provides a measure of the phase difference of the two waves.

Interferometer: An instrument that makes use of the interference of light waves for the purposes of measurement. Different types of interferometers include the Michelson, Fabry-Perot, Mach-Zehnder, and the Sagnac interferometers.

Intromodal dispersion: The combination of material and waveguide dispersion. This type of dispersion is negligibly small in multimode fibers and is only important in single-mode fibers.

Laser (Light Amplification by Stimulated Emission of Radiation): Semiconductor devices that make use of light absorption and emission properties of materials coupled with an optical resonant cavity as a positive feedback mechanism. Semiconductor lasers are made of the same basic materials as light emitting diodes (LEDs), but they emit coherent light, typically with a much narrower spectral width. Because of the narrow spectral width of these lasers, they are well suited for use with single-mode fibers.

Light emitting diode (LED): Semiconductor device composed of two doped materials joined together that emits incoherent light when a voltage is applied in the forward (biasing) direction. These devices are typically made of mixtures of gallium, arsenic, and/or phosphorus and are the simplest and least expensive light sources.

Macrobending (curvature) loss: Loss that occurs in a fiber waveguide when a bend in the fiber has a sufficiently small radius. At this point, the total internal reflection angle (Brewster's angle) is no longer exceeded and light rays in the core escape to the cladding. Multimode fibers are less sensitive to this than single-mode fibers.

Material dispersion: Dispersion or distortion of a pulse in an optical waveguide due to differences in wave velocity caused by variations in the index of refraction for different wavelengths of light and the finite spectral width of the light source.

Because the propagation velocity varies inversely with the index of refraction, the propagation time from the beginning of the fiber to some point in the guide varies directly with the length. The rate of change of index of refraction with respect to wavelength is also a factor in this type of dispersion. Material dispersion has been shown to become negligible when the wavelength of the light source is in the 1.2 to 1.4 micron range.

Microbending loss: Losses in fiber waveguides that result from light scattering due to small abrupt changes in the core's mechanical structure. These irregularities are typically caused during manufacturing.

Modal dispersion: Losses that result from the interaction of different modes of propagation of the same signal within a multimode fiber (waveguide). This form of dispersion may be reduced by use of graded index fibers and may be eliminated by use of a single-mode fiber.

Mode: In a waveguide, transmission line, or cavity, one of the electromagnetic field distributions that satisfies Maxwell's equations and the boundary conditions. The field distribution of a mode depends on the wavelength of propagated light, and the refractive index and geometry of the waveguide.

Monochromatic: A light source consisting of a single wavelength or color. In real light sources, radiation is never perfectly monochromatic, but instead has a narrow band of wavelengths.

Multimode optical fiber: An optical waveguide that will allow more than one bound mode to propagate.

Numerical aperture: A measure of the maximum angle of light entering the end of a fiber that will be propagated within the core of the fiber. The numerical aperture defines the acceptance cone of a fiber.

Optical cavity: A region bounded by two (or more) reflecting surfaces—variously called mirrors, end mirrors, or cavity mirrors—that are aligned to provide multiple reflections within the cavity. A laser uses such a cavity to produce a high-energy beam.

Optical fiber: Any filament or fiber, made of dielectric material, that guides light, whether or not it is used to transmit signals. Typical fibers are made of doped glass.

Optical path length: In a medium of constant refractive index n, the product of the geometrical distance and the refractive index. Optical path length is proportional to the phase shift a light wave undergoes along a path.

Optical repeater: In an optical fiber communication system, a device or module that receives a signal, amplifies it, and retransmits it.

Optoelectronic: Any device that functions as an electrical-to-optical or optical-to-electrical transducer. Examples of optoelectronic devices include photodiodes and semiconductor lasers.

Photodiode: A semiconductor device that produces current in response to impinging light. These devices are used to detect optical power and to convert optical power to electrical power. The two types of photodiodes now used in optical communications are positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes (APDs).

Photon: A quantum of electromagnetic energy equal to the product of the frequency of the electromagnetic (light) wave and Planck's constant.

Planck's constant: A fundamental constant of nature, designated by h, that equates the energy of a quantum of light and the frequency of that light, with value $h = 6.626 \times 10^{-34}$ joule-second.

Positive-intrinsic-negative (PIN): A heterojunction type of photodiode with high quantum efficiency, but no internal gain.

Pulse broadening: A temporal (or spatial) spreading of a pulse that occurs in a waveguide because of chromatic dispersion.

Pulse code modulation (PCM): A modulation technique that uses recurrent pulses quantized into discrete steps of amplitude, frequency, or phase to transmit the information. The main advantage of this technique is that at each repeater a signal identical to the original may be generated, if the presence of noise can be correctly identified.

Quantum efficiency: In an optical source or detector, the ratio of the number of output quanta (usually photons) to input quanta.

Rayleigh scattering: A particular type of scattering that results from variations in the refractive index of the glass, arising from impurities, thermal fluctuations, or density fluctuations that are small compared to the wavelength of the light being transmitted. In Rayleigh scattering, the attentuation is inversely proportional to the fourth power of the wavelength of the propagated light: Loss ~ λ^{-4}.

Refraction: The bending of a light beam when it traverses the boundary between materials of different indexes of refraction. The bending will be towards the normal when the beam crosses the boundary to a material with a higher index of refraction; it will be towards the surface when the index of refraction is lower.

Retromodulator: A device that transmits information by modulating a laser beam from a distant source and reflecting the modulated beam back. The modulation process is accomplished by using the stark effect.

Scattering: A source of power loss in fiber waveguides generally caused by the molecular structure of the (glass) material, and inhomogeneities in the glass. A particular type of scattering, called Rayleigh scattering, occurs when the imperfections in the medium are small in number.

Single-Mode Fiber: An electromagnetic waveguide in which the core diameter is of the same order of magnitude as the wavelength of light. Thus only one mode of light is propagated.

Stark effect: The splitting of a spectral line into multiple lines by the application of an electric field. This effect is due to the shifting of the energy states of electron orbits in an atom that all have the same energy in zero electric field. (Optelecom's retromodulator uses this effect, splitting a single line in fluoromethane (CH_3F) into nine components.)

Tap: A device for extracting a portion of the optical signal from a fiber.

Transmission loss: The total loss encountered in transmission through a system.

Waveguide: A cylindrical body of general cross-section used to trasmit high-frequency electromagnetic radiation (light) with dimension comparable to the wavelength of transmitted radiation.

Waveguide dispersion: The dispersion associated with a nonmonochromatic light source, resulting from the fact that the ratio of core radius/wavelength and consequently the field distributions and group velocities of the modes of an optical waveguide are wavelength dependent. In practice, waveguide dispersion always acts in combination with material dispersion; the combined effect is referred to as intramodal dispersion.

Wavelength division multiplexing (WDM): The process of transmitting two or more wavelengths on the same fiber. Each wavelength represents a data channel. WDM can be either unidirectional or bidirectional. Unidirectional means all the data flow in the same direction. Bidirectional uses a single fiber to transmit data in both directions.

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